SIMULATIONS OF INDUCERS AT LOW-FLOW OFF-DESIGN CONDITIONS

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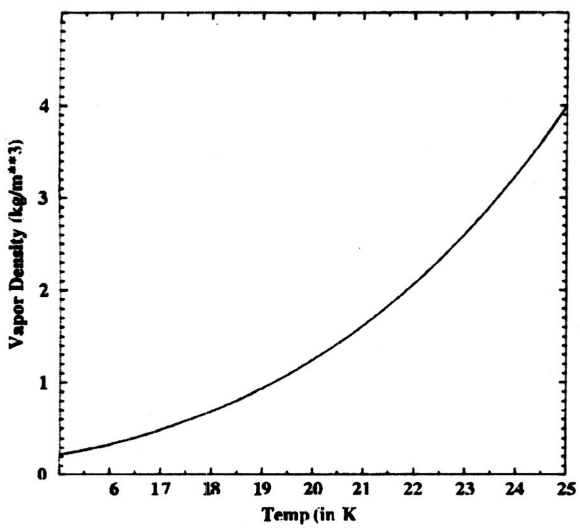
OVERVIEW

- Background on thermal effects on cavitation and numerical framwork
- Validation of Numerical Model for Cryogens in CRUNCH CFD®
  - Comparison with Subscale Test Data of Hord (1973)
- Simulations of Liquid Hydrogen Inducer at Various flow Coefficients
  - 120% of Design, Design, and 80% of Design Flow Rate
  - Detailed Comparisons of Flow Profiles
  - Sensitivity of backflow to turbulent viscosity noted
- Conclusions

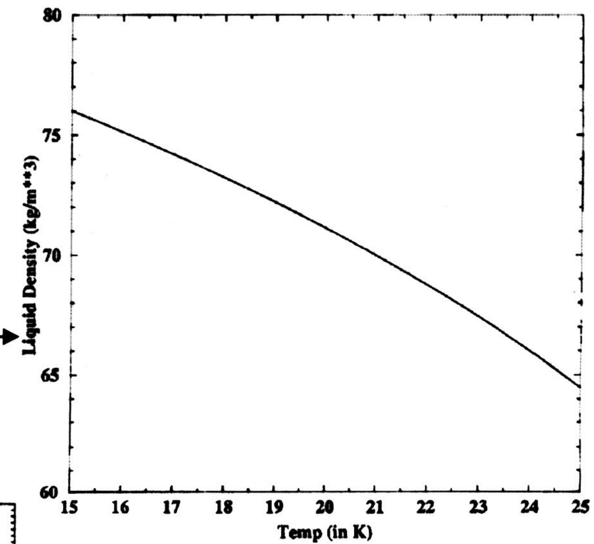
BACKGROUND ON THERMAL EFFECTS IN CAVITATION

- When liquid temperature gets closer to its critical temperature (typical of cryogenic fluids) thermal effects become important
- In this operating regime
  - Vapor pressure and density are much higher. More liquid has to vaporize to sustain mass of vapor in cavity
  - Variation of vapor pressure and density with temperature is significant
- Vaporization results in evaporative cooling effect
  - Maximum Temperature/Pressure Depression at Leading Edge of Cavity
  - Lower Temperatures Result in Lower Cavity Pressures and Improve Mean Performance
- Cavitation zone in cryogenic fluids is visually described as “frothy” and distinct from the “sharp” cavity interfaces observed in water
  - Entrainment into the cavity is also significantly higher for cryogenic fluids
- Reynolds number for cryogenic fluids significantly higher than equivalent water tests
  - Kinematic viscosity smaller by factors of 10-20

PHYSICAL PROPERTIES OF HYDROGEN
(Temperature Dependence)

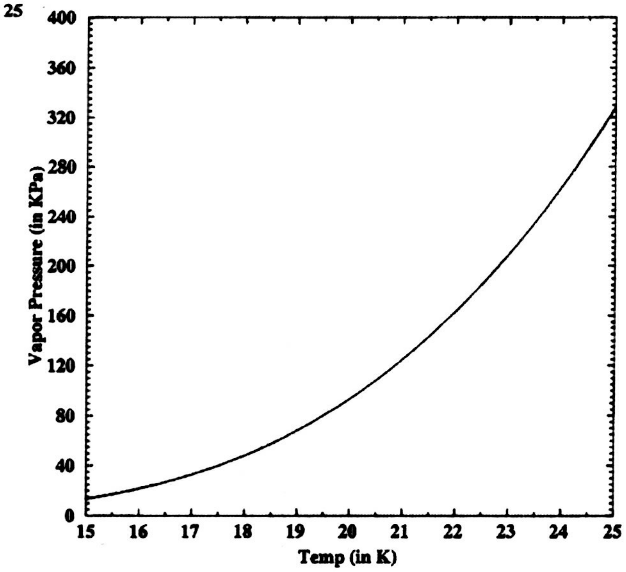


Density Variation with Temperature



Hydrogen Vapor

Liquid Hydrogen



Vapor Pressure

<u>Vapor Pressure Variation</u>

93.25 KPa at 20 K

100.5 KPa at 20.25 K

Slope= 29 KPa/K (Roughly Twice that of Liquid Nitrogen)

MULTI-PHASE CAVITATION FORMULATION WITH THERMAL EFFECTS

- Start with compressible system $\frac{\partial Q}{\partial t} + \frac{\partial E}{\partial x} = S$ (1)

$$Q = \begin{pmatrix} \rho_m \\ \rho_m u \\ \rho_g \phi_g \\ H_m \end{pmatrix} \quad E = \begin{pmatrix} \rho_m u \\ \rho_m u^2 + P \\ \rho_g \phi_g u \\ H_m u \end{pmatrix} \quad S = \begin{pmatrix} 0 \\ 0 \\ m_t \\ m_t \Delta h_{fg} \end{pmatrix} \quad \begin{aligned} \rho_g &= f_g(P,T) \\ \rho_l &= f_l(P,T) \\ \rho_m &= \rho_g \phi_g + \rho_l \phi_l \\ H_m &= \rho_g \phi_g h_g + \rho_l \phi_l h_l \end{aligned}$$

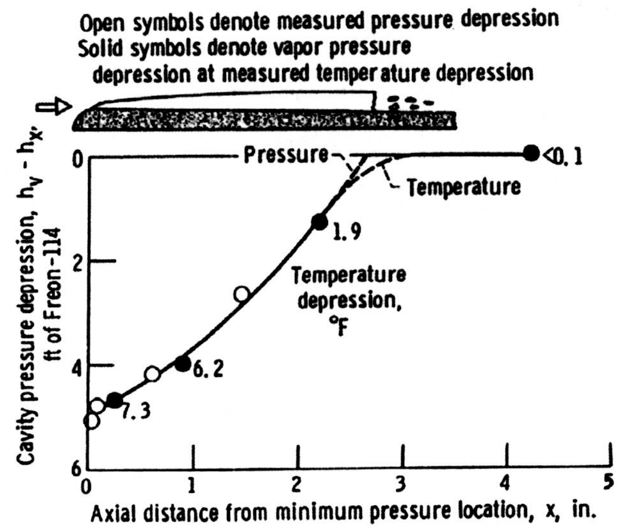
  - Energy equation neglects pressure work ("low speed" approximation)

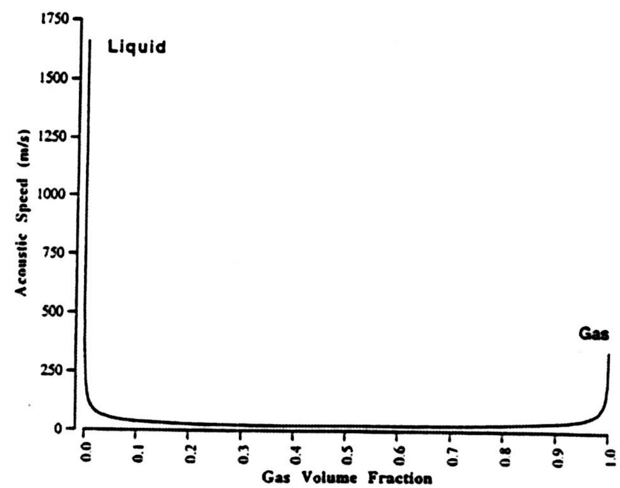
- Rewrite Eqn. (1) in pressure-temperature based form using EOS as

$$\Gamma \frac{\partial Q_V}{\partial t} + \frac{\partial E}{\partial x} = S, \quad \left\{ Q_V = \begin{bmatrix} p \\ u \\ \phi_g \\ T \end{bmatrix} \right\}, \; \Gamma = \frac{\partial Q}{\partial Q_V}$$

SOLUTION PROCEDURE

- Physical and thermodynamic properties for vapor and liquid specified as a function of saturation temperature
  - Tabular data generated from NIST database for various cryogenic fluids
- System is Stiff With Large Variations in Acoustic Speed
  - Preconditioning used to obtain an efficient integration procedure
- Cavitation Source Terms Specified Thru Finite Rate Phase Change
- More Rigorous Unsteady Bubbly Model For Dense Vapor Clouds Under Development



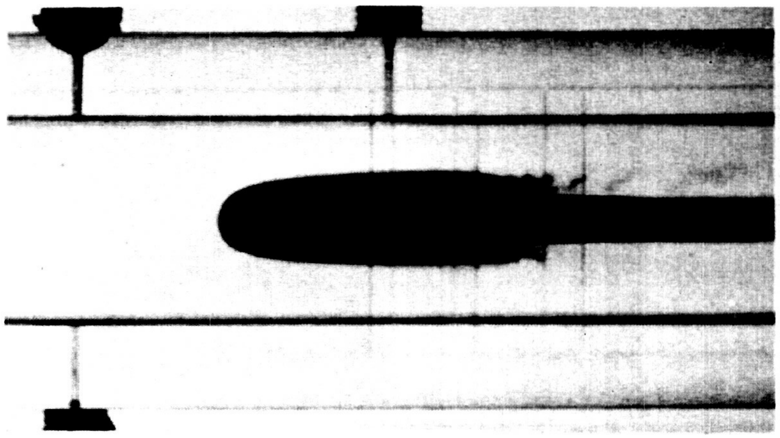


LIQUID HYDROGEN INDUCER SIMULATIONS

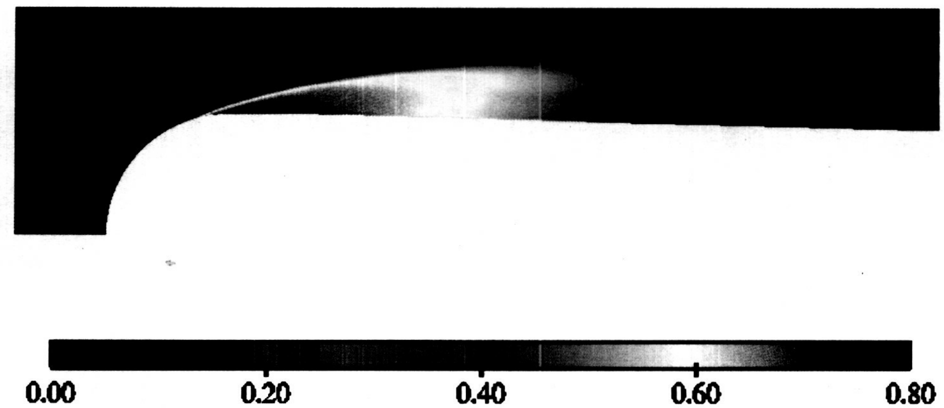
- Detailed Validation for Liquid Nitrogen and Hydrogen in Hydrofoil and Ogive
  - Compared Temperature and Pressure Depression Profiles with Experimental Data of Hord (1973)
- Simulation of RS-84 Inducer at Design Conditions
  - Sub-scale Water and Full Scale LOX Configuration modeled thru Breakdown
  - Suction Performance Improvement due to Thermal Effects Identified
- Simulations of Randy's Inducer at Off-Design Conditions
  - Inducer Back Flow at Low-Flow Conditions Modeled
  - Detailed Comparison of Velocity and Pressure Profiles Upstream of Inducer with Experimental Data From CNREC
- Unsteady Cavitation Model Developed and Tested on Ogive
  - Lack of unsteady data in cryogenic fluids

CAVITATING HYDROFOIL FLOWFIELD

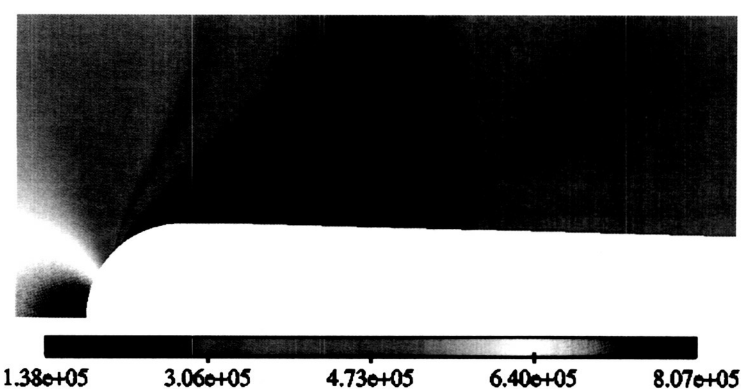
Flow Visualization



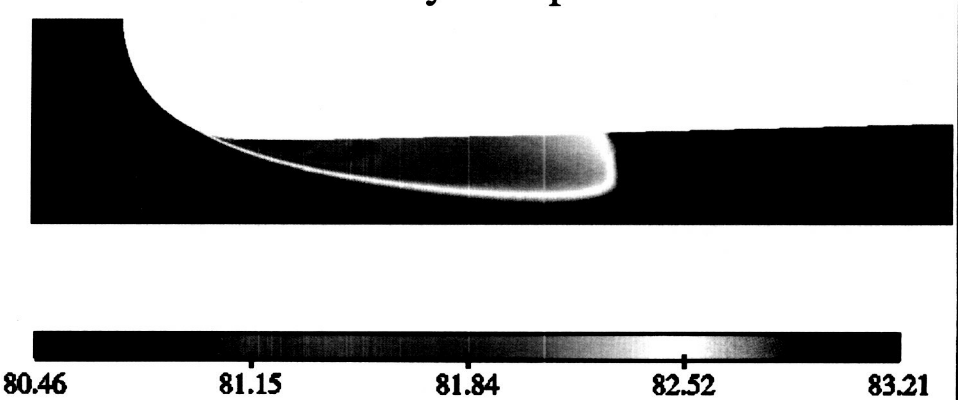
Vapor Volume Fraction



Pressure Distribution



Cavity Temperature



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CAVITATING HYDROFOIL: LIQUID NITROGEN

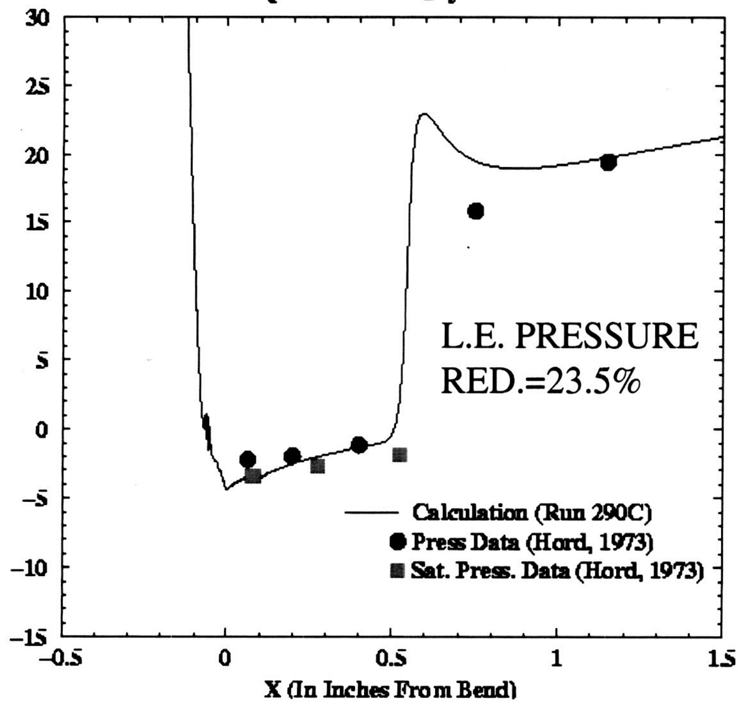
BASELINE CALCULATION (RUN 290C) CONDITIONS

Temperature = 83.06 K
Velocity = 23.9 m/s
Pressure = 56.83 N/cm2
Vapor Pressure = 18.86 N/cm2

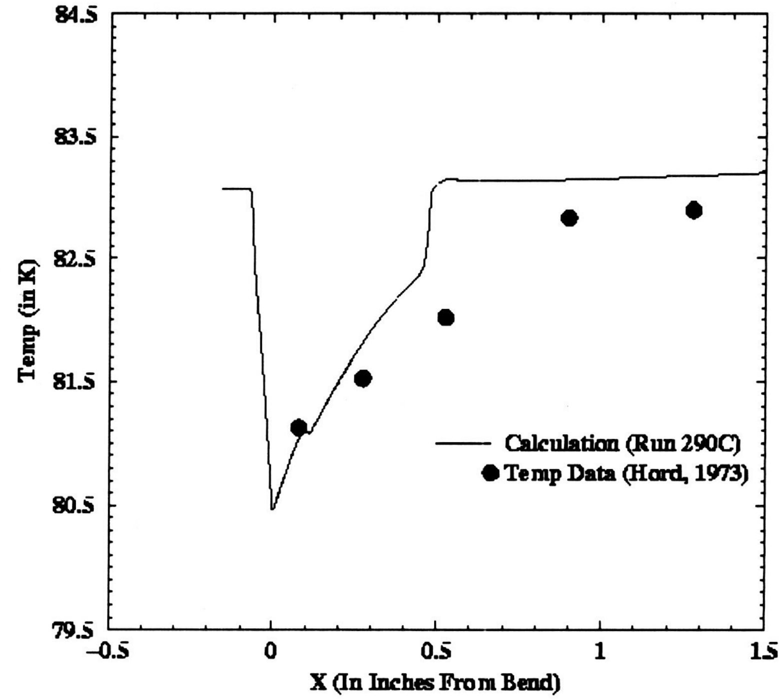
INSTRUMENTATION ERROR BAR

Chromel-Gold Thermocouple: 0.20 K Error
Pressure Transducer: 0.69 N/cm2

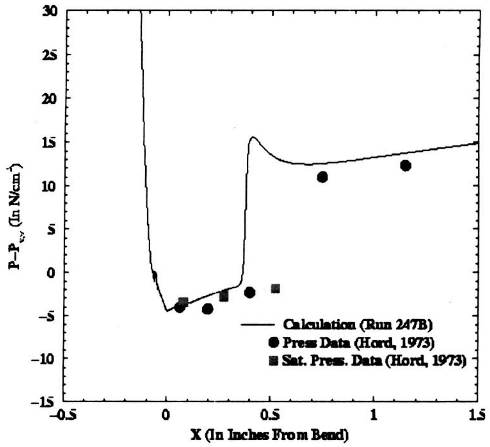
Pressure Depression



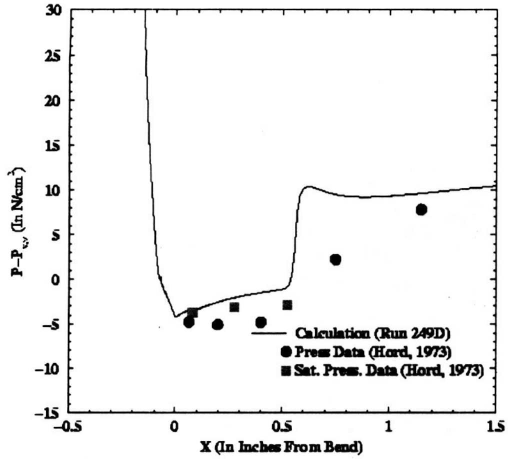
Temperature Depression



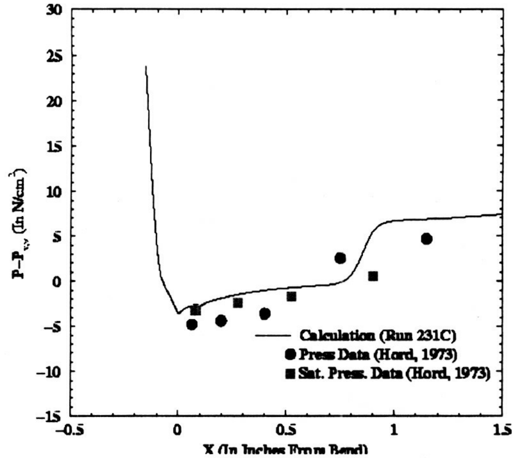
CAVITATING HYDROFOIL: LIQUID HYDROGEN



L.E. Press. Depress. = 39%



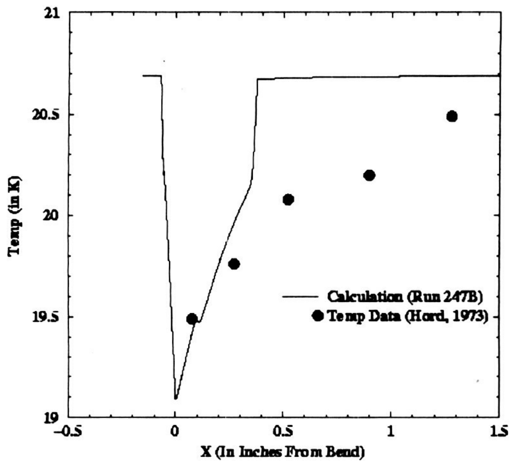
L.E. Press. Depress. = 36.2%



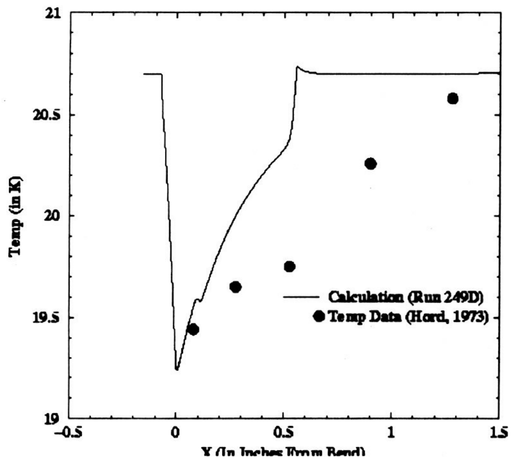
L.E. Press. Depress. = 33.4%

Pressure Depression

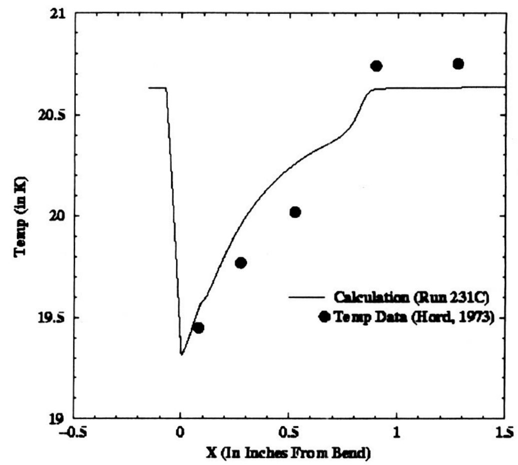
Liquid Hydrogen



Temp= 20.69 K, Vel=65.2 m/s
Cavitation Number= 1.68
Cavity Length=0.6 in



Temp= 20.70 K, Vel=58.1m/s
Cavitation Number= 1.57
Cavity Length= 0.75 in



Temp= 20.63 K, Vel=51.4m/s
Cavitation Number= 1.34
Cavity Length= 0.70 inches

Temperature Depression

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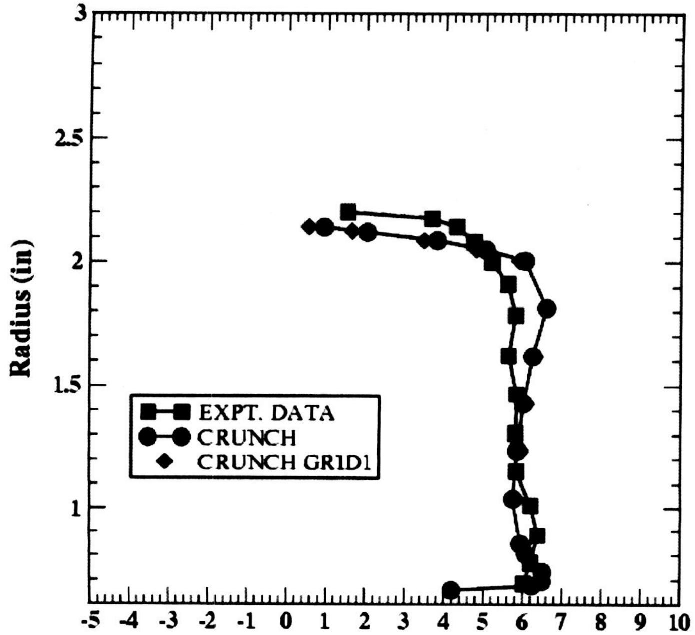
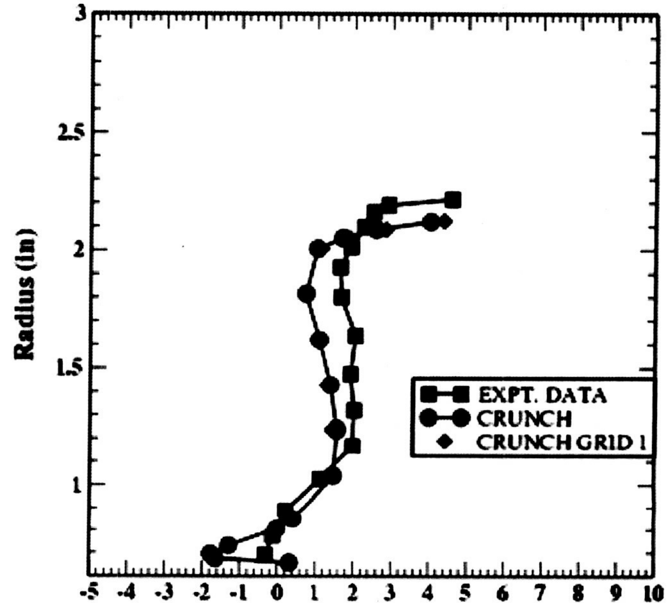
SIMULATIONS OF LIQUID HYDROGEN INDUCER

- Calculations performed at RPM of 3840, Tip Gap 0.014 inches
  - Flow Rates: 235 gpm (120%Design), 195 gpm (Design), 155 gpm (80% Design)
- Solution Profiles Upstream of Leading Edge Compared With experimental data
  - Radial profiles compared with experimental data to verify extent of backflow in solution
  - Sensitivity of the back-flow to turbulence model studies
  - Profiles at leading edge of the blade
  - Exit deviation angles compared with experimental data

120% DESIGN: INLET FLOW VELOCITY



Meridional Velocity



Incidence Angle to Blade Leading Edge

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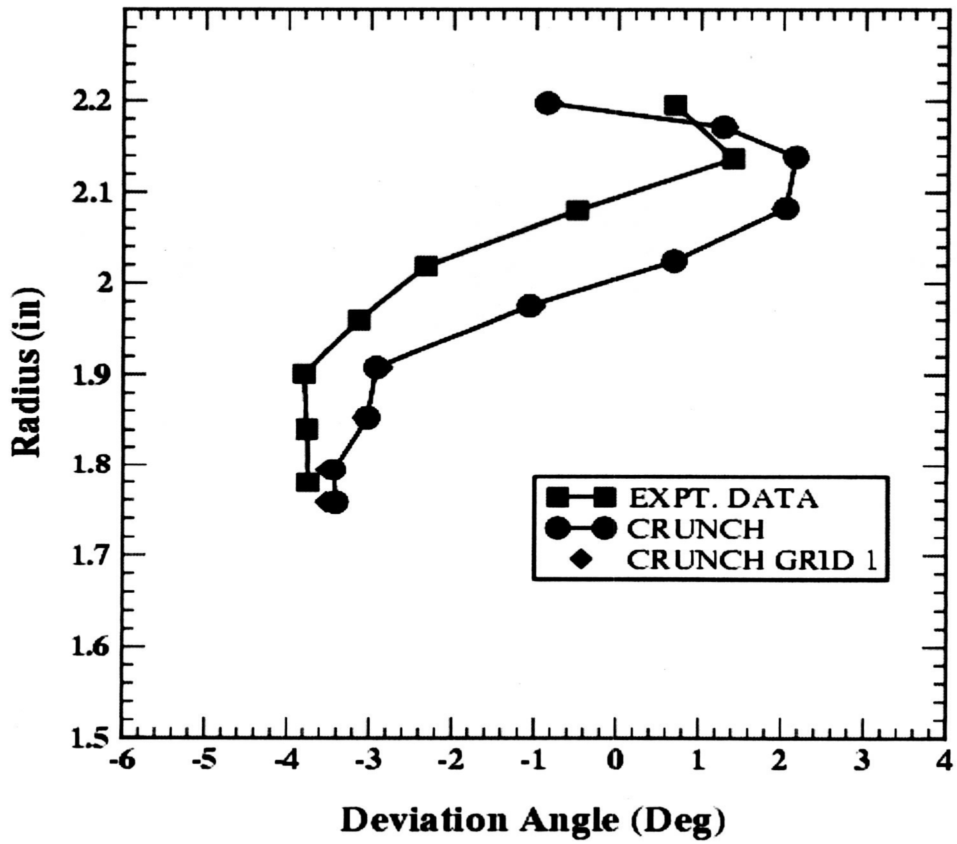
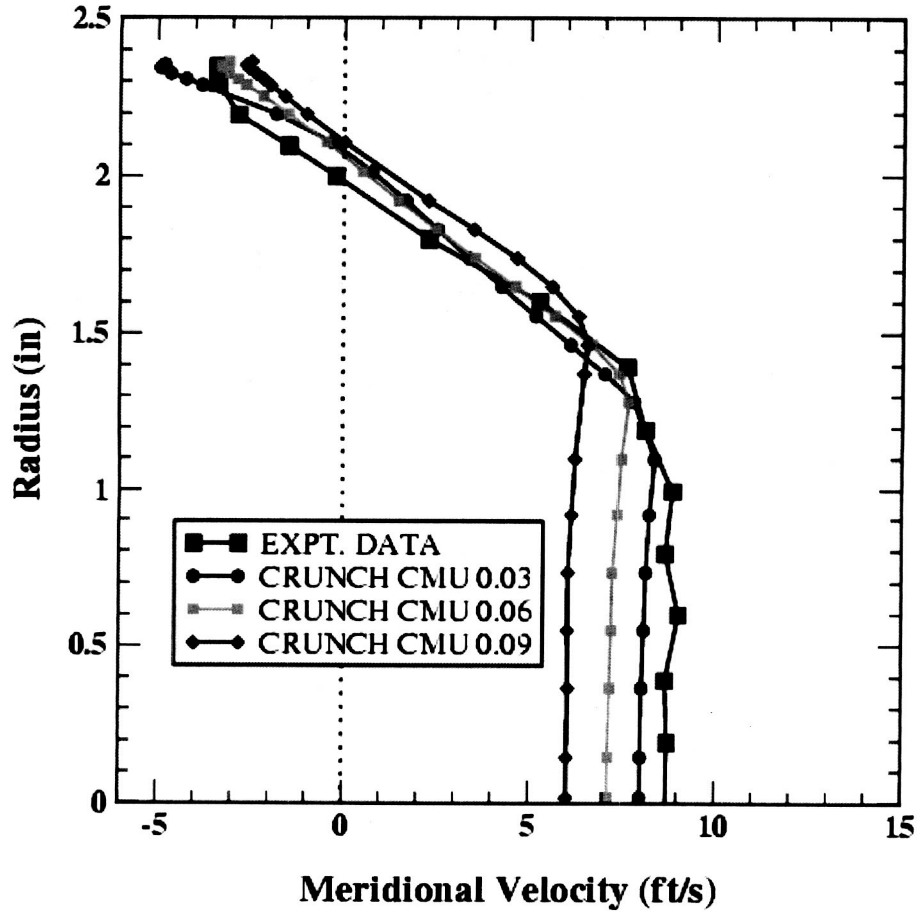
120% DESIGN: EXIT FLOW VELOCITY



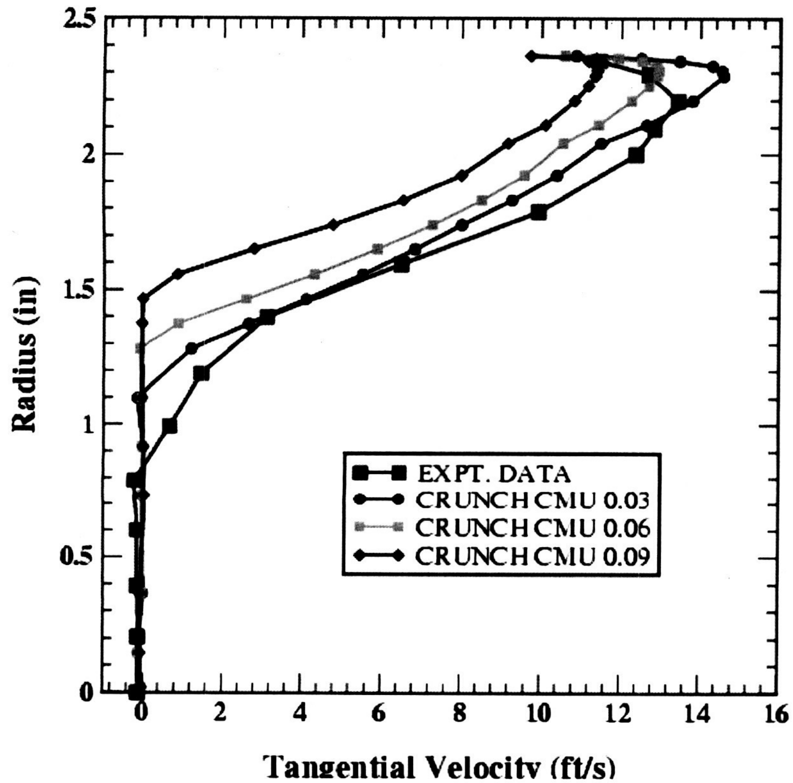
Deviation of Flow Vector From
Blade Angle At Exit

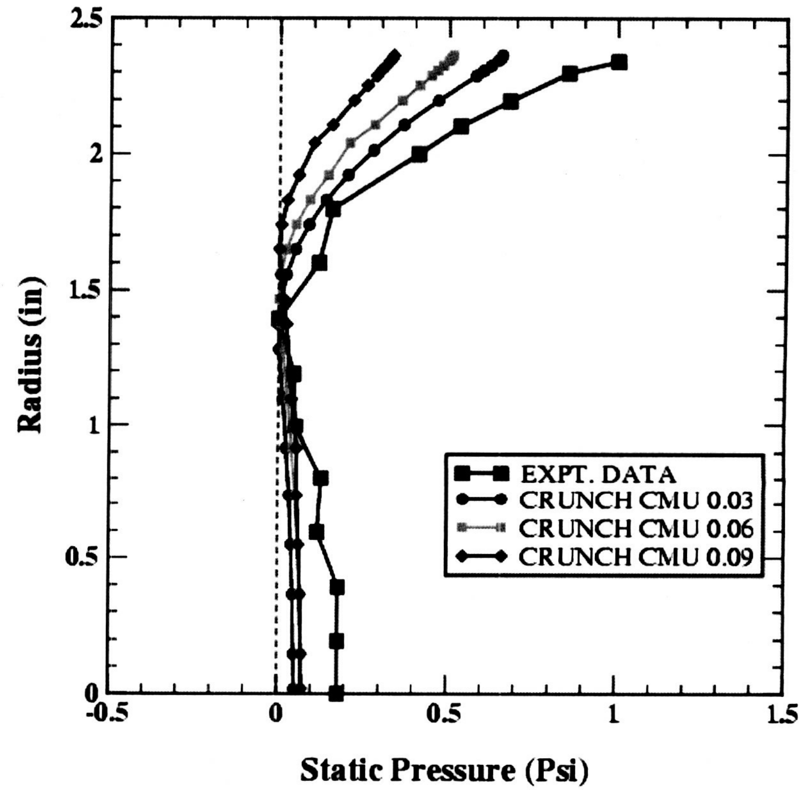
DESIGN CASE: MERIDIONAL VELOCITY



Comparison with Data Half a Diameter Upstream of Inlet

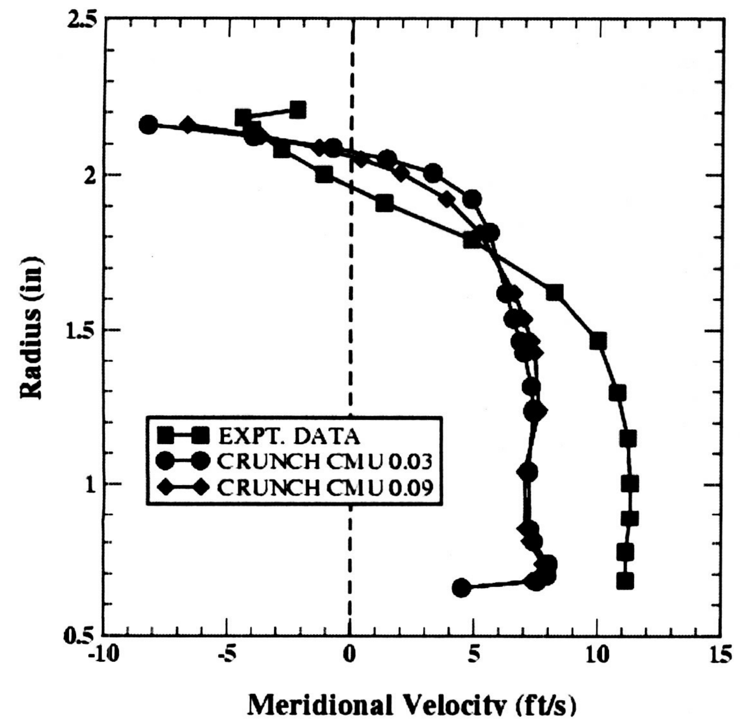
DESIGN CASE: SWIRL AND PRESSURE

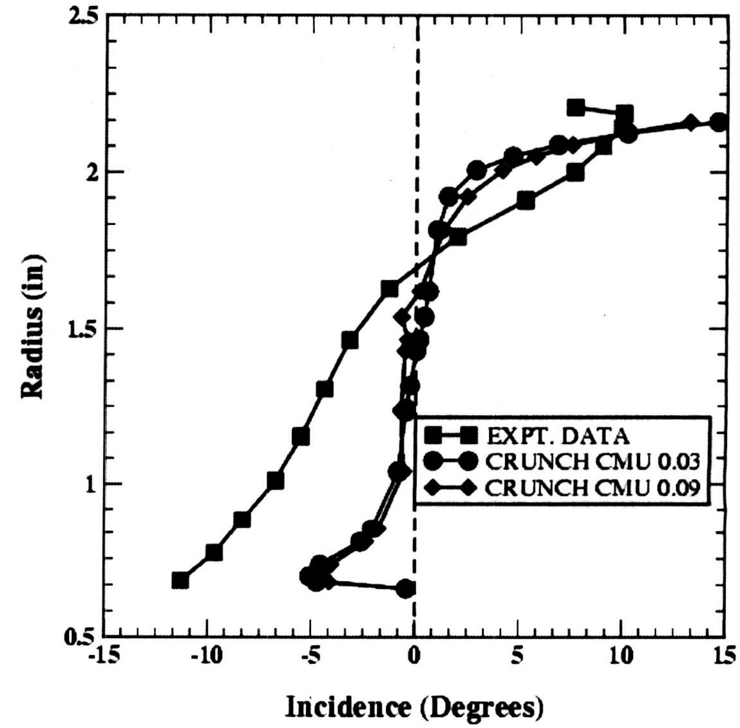




Comparison with Data
Half a Diameter
Upstream of Inlet

DESIGN CASE: BLADE INLET FLOW VELOCITY





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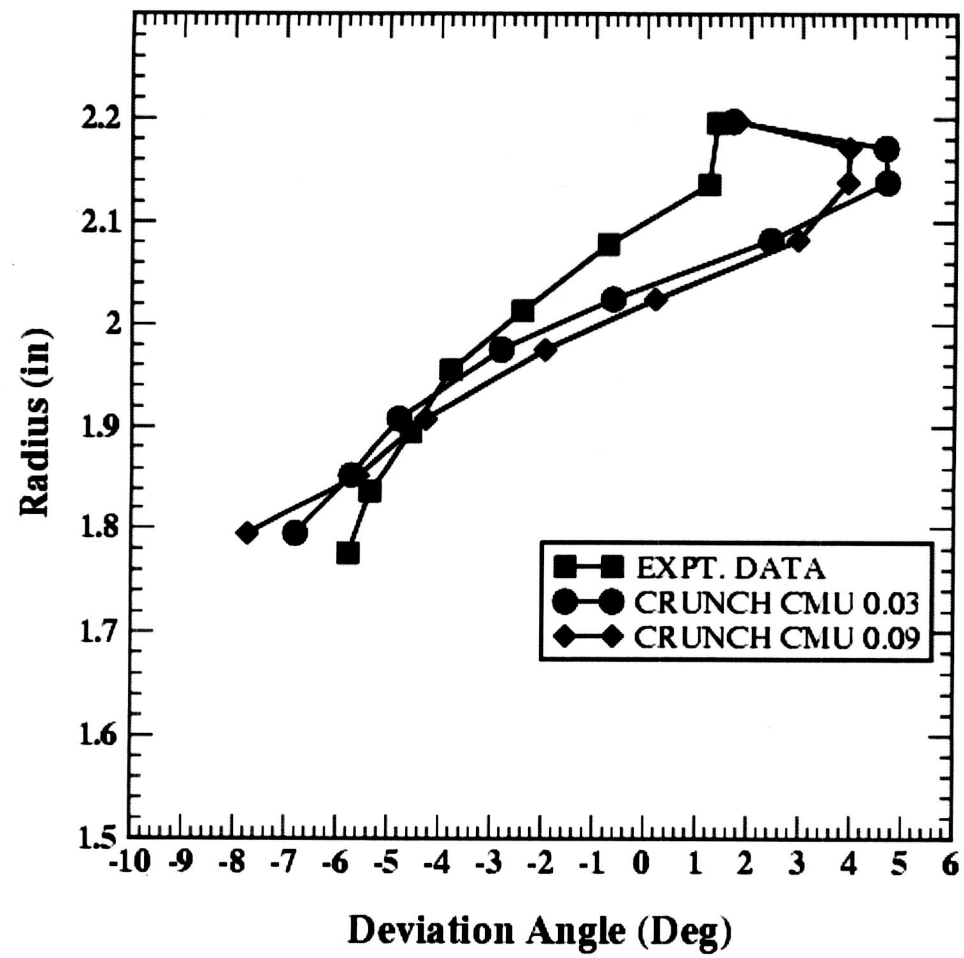
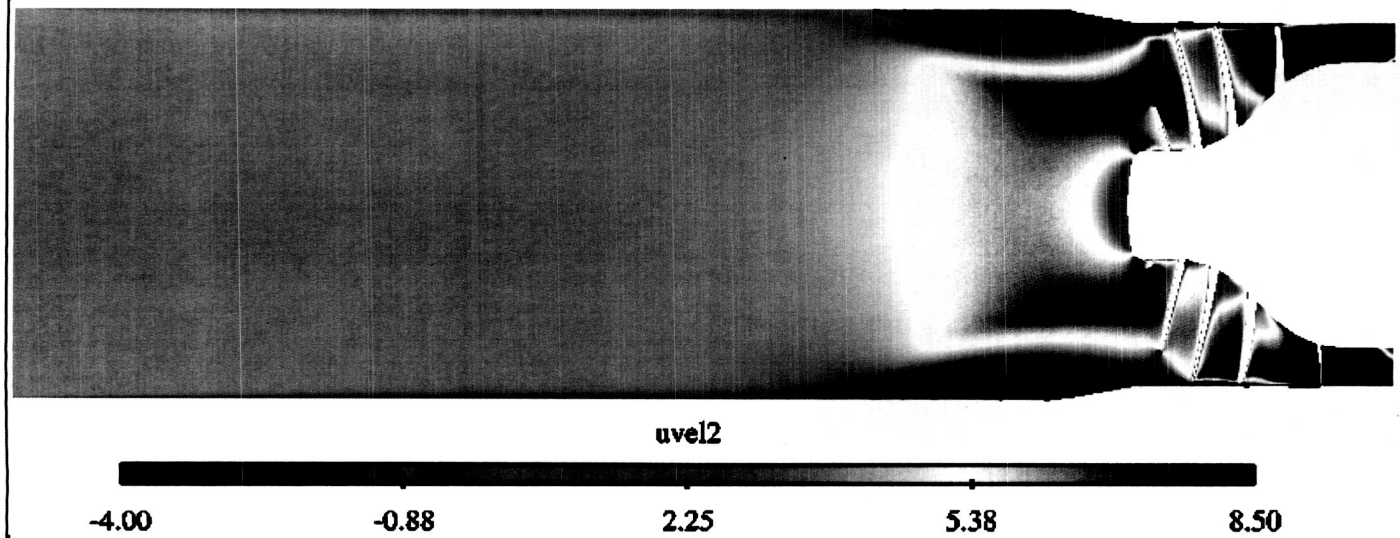
DESIGN CASE: EXIT FLOW VELOCITY



Deviation of Flow Vector From
Blade Angle At Exit

DESIGN CASE: MERIDIONAL VELOCITY



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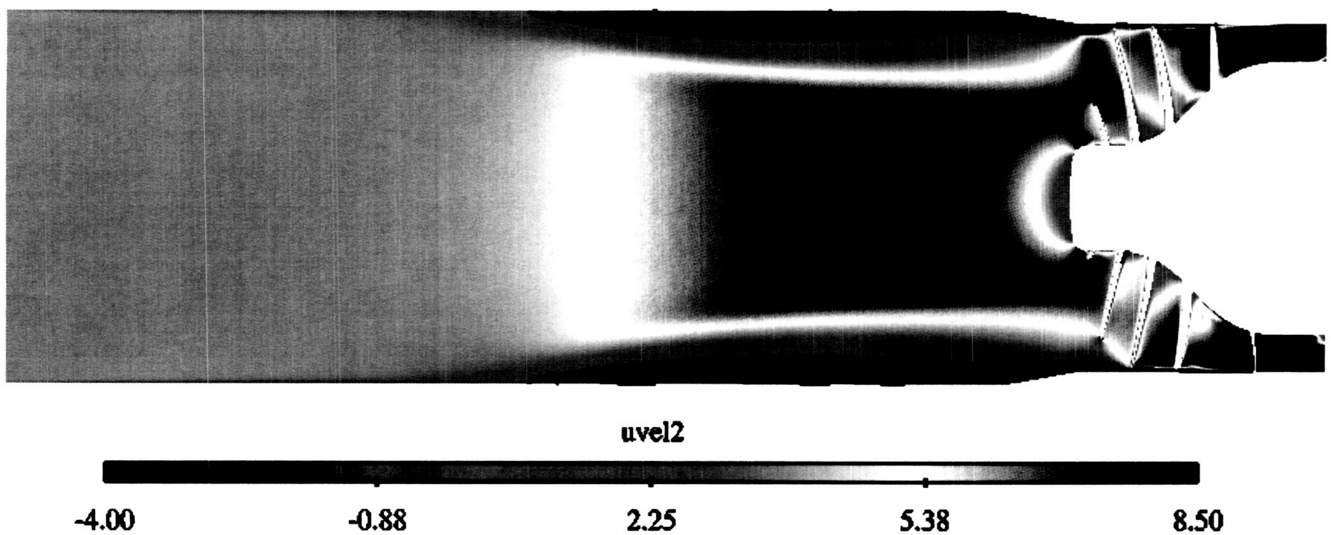
Meridional Velocity
ft/s



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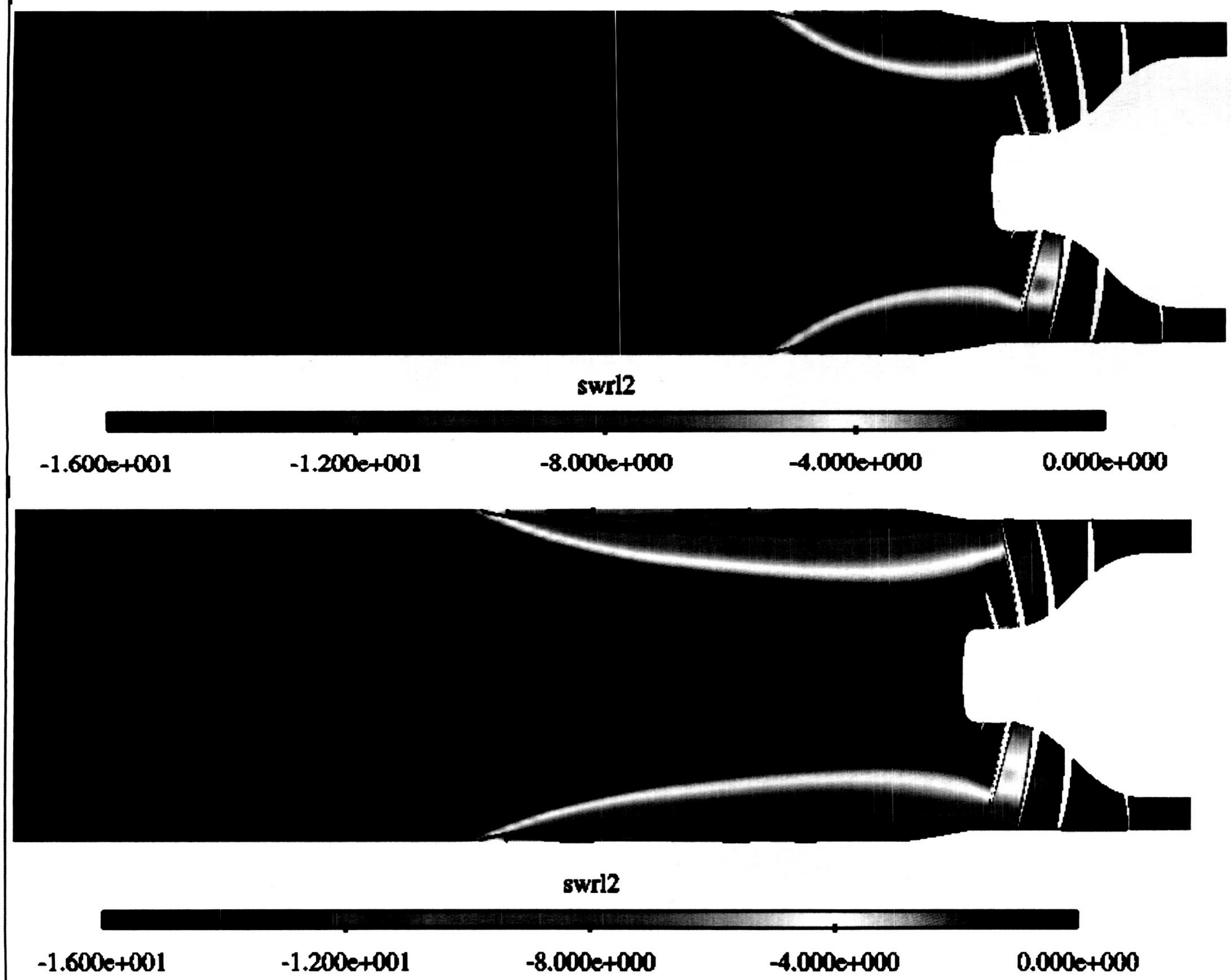
DESIGN CASE: TANGENTIAL VELOCITY



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Tangential Velocity
ft/s

[redacted]

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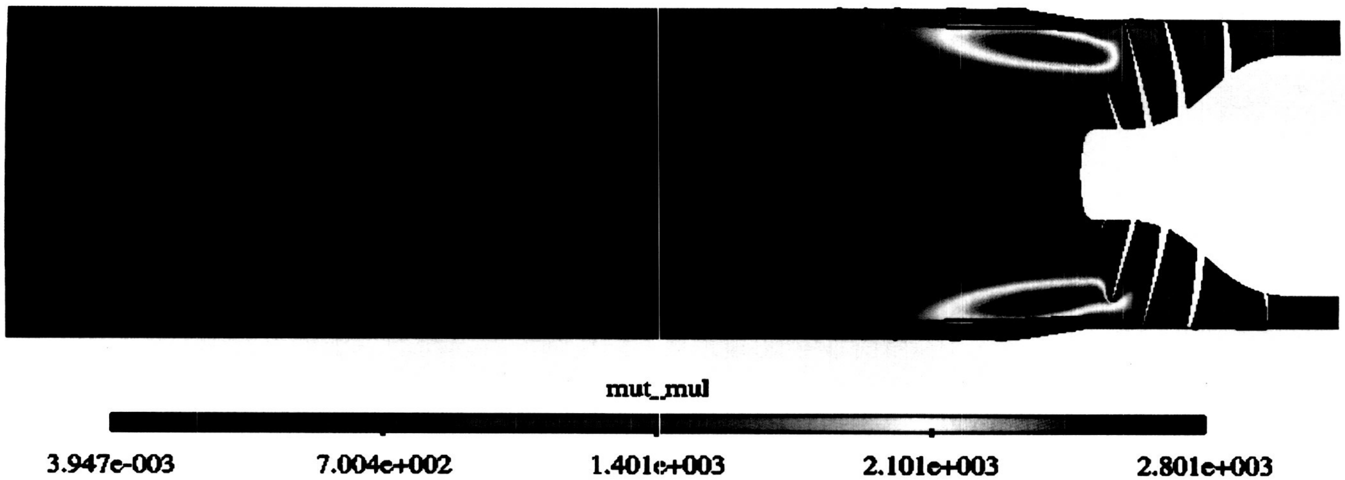
DESIGN CASE: TURBULENT VISCOSITY



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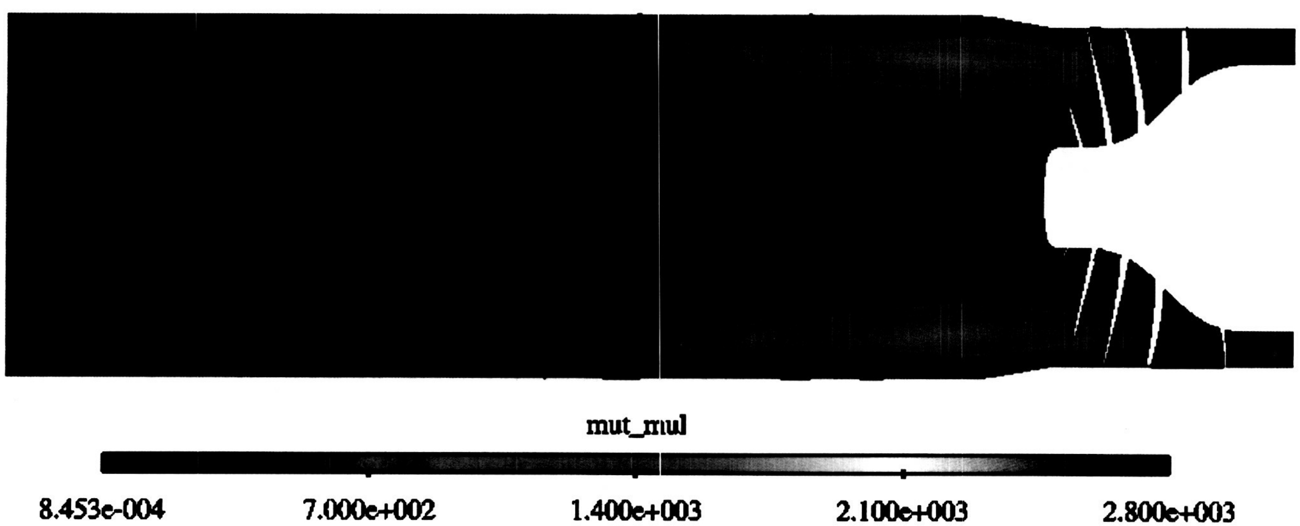

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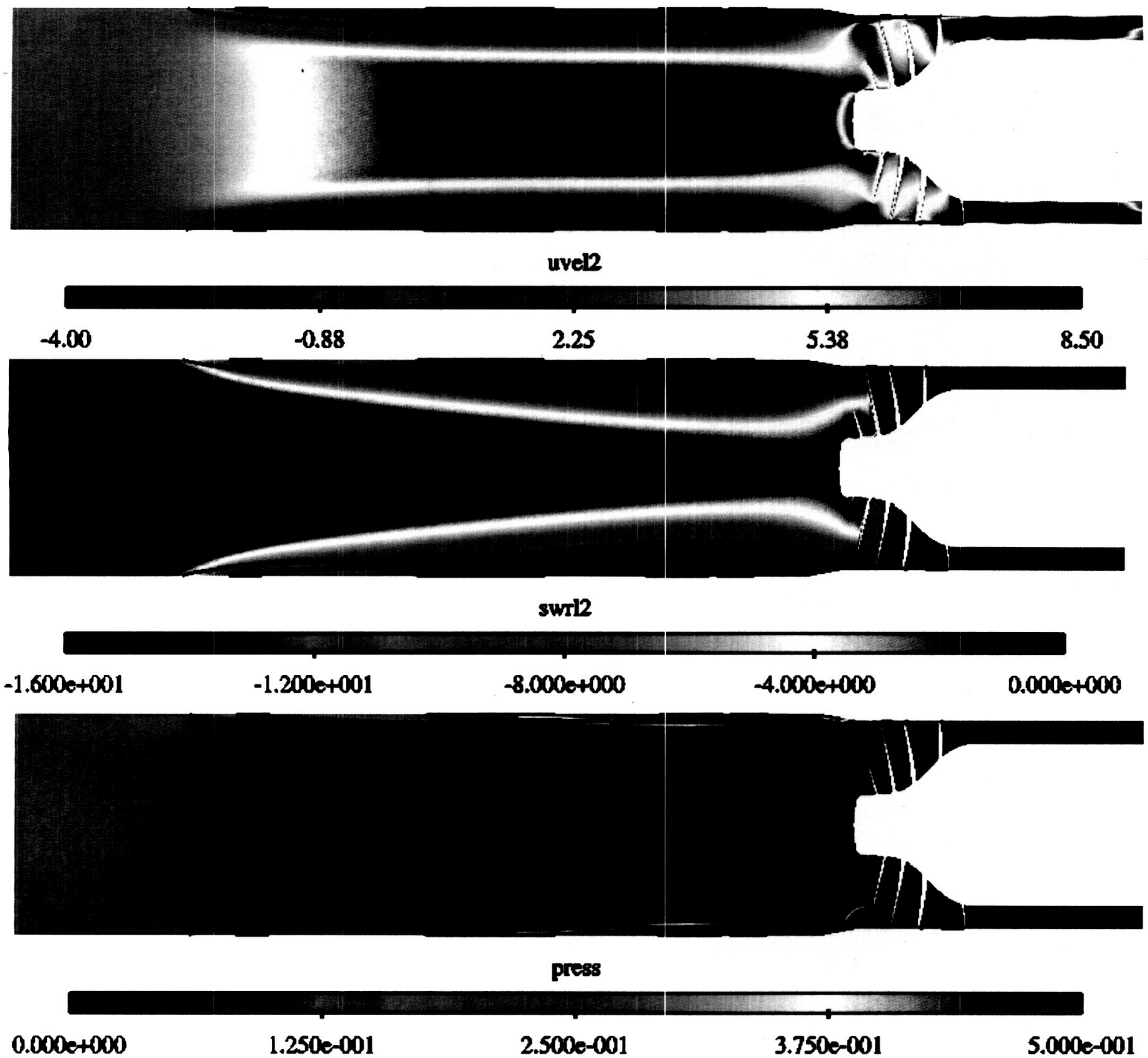
80% OF DESIGN CASE



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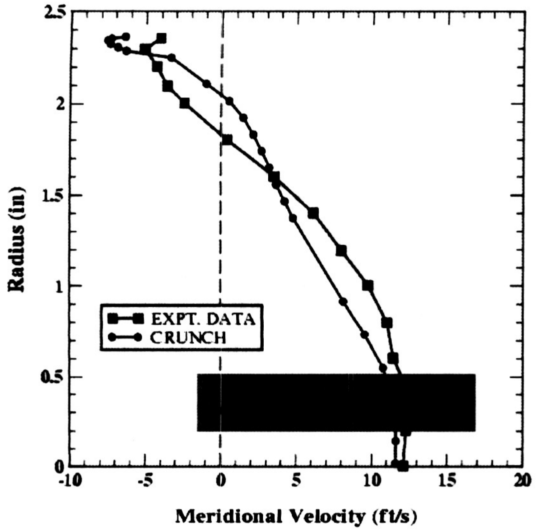
80% OF DESIGN CASE : COMPARISONS WITH DATA



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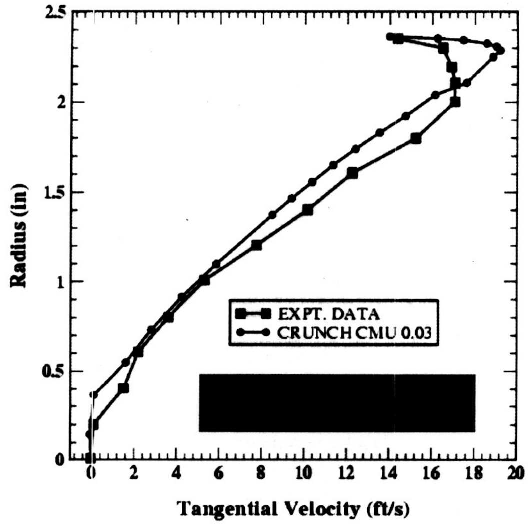

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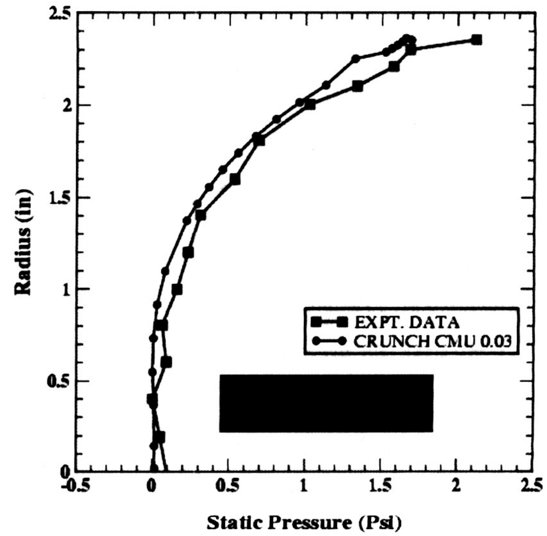

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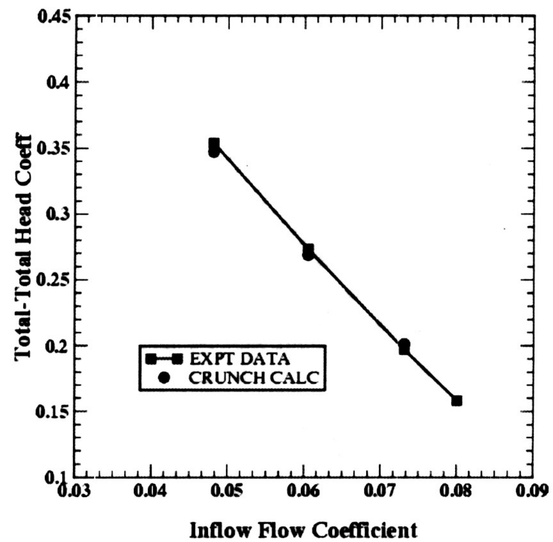

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SUMMARY

- Simulations of a 3-bladed liquid hydrogen inducer tested in water have been performed with CRUNCH CFD
- Calculations performed at various Flow Coefficients at RPM of 3840, Tip Gap 0.014 inches
  - Flow Rates: 235 gpm (120%Design), 195 gpm (Design), 155 gpm (80% Design)
- Solution Profiles Upstream of Leading Edge Compared
  - For low-flow cases best comparison obtained for lowered levels of turbulent viscosity which yield larger separation lengths
  - Comparison good for Axial velocity and swirl
  - Strong radial pressure gradients generated in backflow region that makes the flowfield susceptible to cavitation surge
- Profiles at blade inlet seem insensitive to the differences in the separation length